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An Evaluation of Scattering-Type Visibility Instruments

DONALD A. CHISHOLM
LEO P. JACOBS

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An evaluation of three scattering-type visibility instruments has been made under wide ranging weather conditions at a test site near Hanscom AFB, Mass. The sensors tested were the EG+G Forward Scatter Meter (FSM), the Impulsphysik Videograph, and the MRI Fog Visiometer. Data were gathered during periods of fog, rain, and snow in order to calibrate the Videograph and Fog Visiometer to the extinction coefficient output of the FSM and to develop correlation and error of estimation statistics between the outputs of the three sensors. Consideration was given to the suitability of the instruments for use.		

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20. Abstract (continued)

in remote and fully automated weather observation systems. The calibration of the Videograph is considerably different in snow as compared with other weather restrictions. The Fog Visiometer has limited usefulness in snow (particularly when the air temperature is near freezing) and performs poorly in light rain. During the period of the 4-month test all three instruments performed well with only limited downtime due to component failure.

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An Evaluation of Scattering-Type Visibility Instruments

1. INTRODUCTION

In this report results of a comparative evaluation of three atmospheric visibility sensing devices are presented. They are the forward scatter visibility meter (FSM) developed by EG+G Inc., a backscatter device (Videograph) developed by Impulsphysik GmbH, and a total scatter device called the Fog Visiometer which was developed by MRI (Meteorology Research Inc.). The objective of the study was to evaluate automated sensors of visibility and runway visual range as part of a project designed to determine the feasibility of developing a fully automated surface weather observation capability to meet the present and future needs of the Air Force. The tests were conducted at a site in the Hanscom mesonetwork within a mile of the runways at Hanscom AFB, Mass. Performance data were gathered nearly continuously from mid-November 1974 through early April 1975. Data used in the comparative analysis included those episodes of snow, rain, and advection fog or stratus which reduced visual range below 2 miles for periods of 2 hours or longer.

An evolutionary process, which has taken place at AFCRL over the past 5 years, has led to this study. In the initial stages of the process, alternative sensing devices to the transmissometer were sought. Small volume scattering devices offered an attractive alternative due to their single-frame construction

(Received for publication 30 July 1975)

which eliminates alignment problems and facilitates installation in remote and confining locations. Exhaustive tests of the FSM demonstrated a high correlation between its extinction coefficient and transmittance measures of the transmissometer and human visibility observations under a wide range of visibility restriction causes. The problems of background illumination, contrast thresholds, human visual acuity, and the like, which must be considered along with the sensor measurement of transmittance or extinction coefficient in order to arrive at visibility and runway visual range, would, therefore, be common to both measurements systems. Continued testing and evaluation of the FSM as part of the Hanscom mesonetwork experiments¹ has led to the conclusion that it provides reliable, accurate, and representative measurements of atmospheric extinction coefficient. Therefore it can legitimately be used as the basis for comparison of the other scattering devices considered in this study.

2. INSTRUMENT DESCRIPTION

Each of the instruments used in this study was a production model as purchased from the manufacturer. In the case of the Videograph and Fog Visiometer, one unit of each was tested and the results presented in the following sections must be viewed in that light. However, every effort was made to adhere to the manufacturer's recommended calibration and maintenance procedures. The FSM used in the evaluation was but one of 27 dispersed throughout a mesonetwork of automated weather stations, established in eastern Massachusetts to assess the short-term predictability of visibility for aviation purposes.¹ In this way inter-comparisons with other FSMs could be and were routinely made.

2.1 Forward-Scatter Visibility Meter (FSM)

The development of the FSM has been treated in detail previously,² therefore a broad overview will be presented here. The FSM is a short-path length visibility instrument developed by the Cambridge Systems Division of EG&G Inc., Bedford, Mass. The instrument (shown in Figure 1) consists of a projector and receiver mounted in a single frame structure designed to minimize the likelihood of heat plumes rising from the control unit and altering the restriction to visibility in the sampling volume. Figure 2 is a schematic illustration of how the FSM operates. The projector consists of a halogen lamp operated by a 120-V, 60-Hz

1. Hering, W.S., Brown, H.A., and Muench, H.S. (1972) Mesoscale forecasting experiments, BAMS 53(No. 12):1180-1183.
2. Muench, H.S., Moroz, E.Y., and Jacobs, L.F. (1974) Development and Calibration of the Forward Scatter Visibility Meter, AFCRL-TR-74-0145.

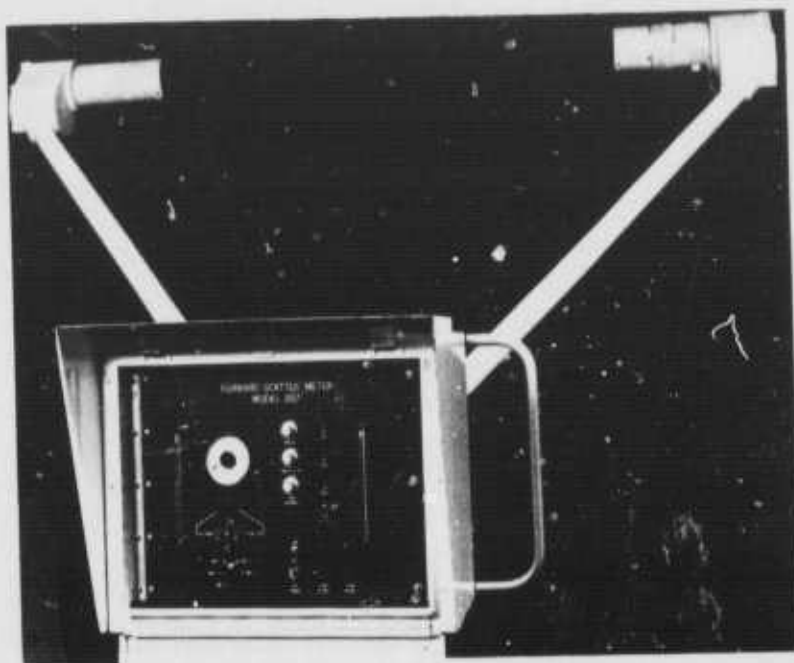


Figure 1. Forward-Scatter Visibility Meter, EG+G

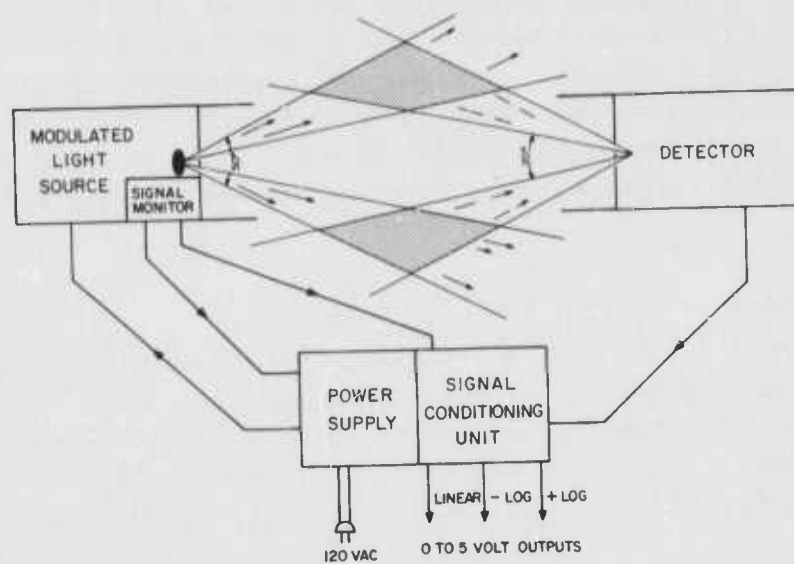


Figure 2. Schematic Diagram of the Forward-Scatter Visibility Meter

regulated power supply. The projected light beam is mechanically chopped before entering the optical system, which projects a cone of light. A photodiode monitors the light, providing feedback to the power supply and timing information to the receiver circuitry. The receiver is mounted and aligned with the projector at a separation distance of about 1.2 m. It consists of a photodiode that receives light from a cone-shaped volume similar to that of the projector. Both the projector and receiver sampling volume have an inner cone masked out to prevent direct transmission of light. The intersection of the projection and viewing cones forms a sampling volume of 0.05 m^3 , which contains light scattered forward over a range of 20 to 50 degrees by particulates within the volume.

The instrument has one linear and two log outputs each with a 0- to 5-V range. Routinely data are collected from the log output channels. The positive log channel covers the range of extinction coefficients from $44 \times 10^{-5} \text{ m}^{-1}$ to $4400 \times 10^{-5} \text{ m}^{-1}$ which corresponds to from 6 km to 60 m daytime visibility. The negative log channel covers the range from $0.44 \times 10^{-5} \text{ m}^{-1}$ to $44 \times 10^{-5} \text{ m}^{-1}$ (6- to 600-km daytime visibility).

Several deficiencies had been uncovered and corrected during the early phases of the experiments involving the Hanscom mesonetwork. They include: (1) changing the frequency of modulation from 12 Hz to 290 Hz which eliminated a background light modulation problem that occurred with partly cloudy skies or bright skies with moderate wind, (2) inserting a cylindrical Pyrex shield over the projector's halogen lamp to prevent internal blackening due to excessive cooling of the lamp by the mechanical chopper, which inhibited the normal halogen reaction, (3) replacing the original photodiodes, which were found to be either not stable enough or not environmentally suitable, with a very stable, more costly diode with a long lifetime, and (4) placing heating straps over the projector and detector hood to prevent snow clogging, which was a particular problem during periods of heavy, wet snow.

2.2 Videograph

The Videograph is a visibility sensor which operates on an atmospheric backscatter of light principle. It was developed by Impulsphysik GmbH, Hamburg, Federal Republic of Germany³ with manufacture in the United States handled through license by the Radiation Division of Harris-Intertype Corporation, Melbourne, Florida.

3. Früngel, F. (1969) The Videograph, backscatter fog detector and visibility meter, Bull. de l' A.I.S.M., No. 40, April 1969, pp 9-16.

The Videograph (Figure 3) includes a projector and receiver housed in a common aluminum housing with internal optical shielding from one another. The light source of the projector is a Xenon flash lamp powered by a solid state voltage regulator which maintains a constant flash rate with a flash duration of about 1 μ sec. Lamp longevity (typically several years) is enhanced by the short flash duration. A heated glass cover and hood extension prevent the accumulation of snow, ice, and condensation on the lamp and reflector.

The projector is inclined upward at an angle of 3° (see Figure 4), which allows the projected beam to intersect the optical axis from the detector at a distance of about 5.7 m from the detector. The scattering volume extends over a range from 3 to 25 m, with the greatest contribution coming from aerosol particles scattering the projected beam backward at a distance of 5.7 to 8 m.

The receiver detector is a solid state photodiode sensitive to the backscattered light pulses of about 1- μ sec duration. A quartz lens system focusses the back-scattered light on the photodiode surface. The receiver unit has a heated glass cover similar to the projector which protects against snow, ice, and condensation. Stray light interference is reduced by limiting the incident angle of received light to less than 10 min of arc through a honeycomb filter arrangement. Output scale is 0 to 5 V.

The Videograph has been tested extensively by the National Weather Service (NWS) of the National Oceanic and Atmospheric Administration⁴ in the United States. They conducted thorough engineering tests to evaluate the performance of the Videograph in temperature and humidity extremes, voltage and frequency variations, waterproof capacity, and finally to determine an average response time for the instrument. These tests showed that although there was a slight drift in recorded output, the instrument performed acceptably over the manufacturer's specified ranges of temperature and humidity. The voltage and frequency tests revealed no detectable changes in output and there was no evidence that precipitation could enter the sensor in the water tests. The time constant tests reveal a response time of 2 min 55 sec to a rapid decrease in visibility and an average response time of 1 min 20 sec to rapidly improving visibility.

2.3 Fog Visiometer

The Fog Visiometer (Figure 5) is a small volume visibility sensor which integrates light scattered over the range 7 to 170°. It is manufactured by Meteorology Research Inc. (MRI), Altadena, California. Like the FSM and Videograph, it has a single frame structure which houses both projector and

4. Observation Techniques Development and Test Branch (1973) Videograph Calibration, Lab Rpt No. 4-73, Task No. 2159-10-31.

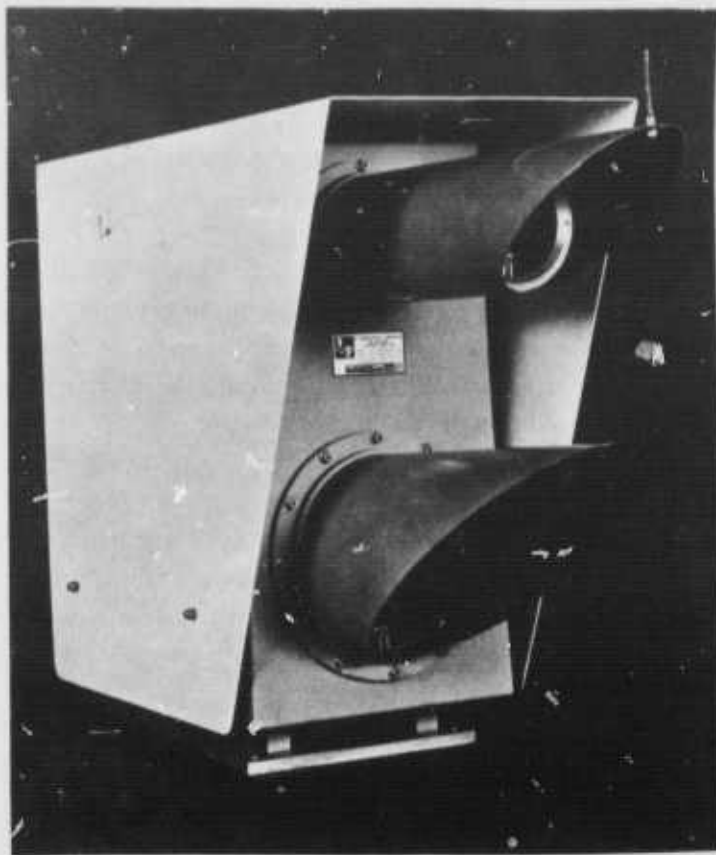


Figure 3. Videograph, Impulsphysik GmbH

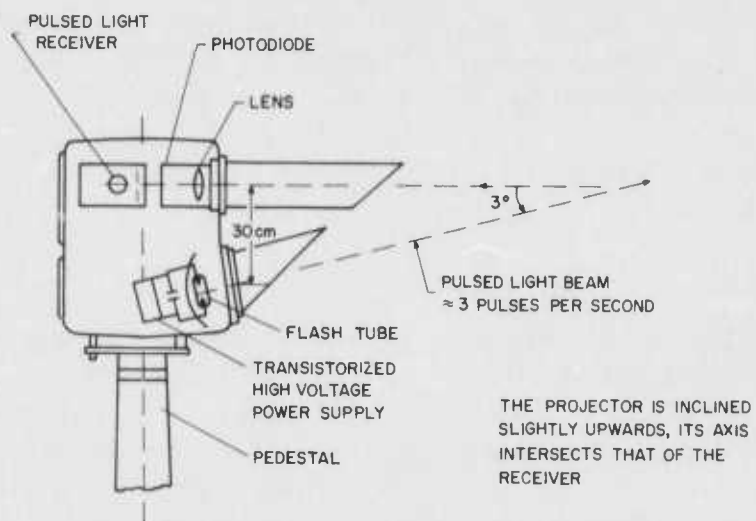


Figure 4. Schematic Diagram of Videograph

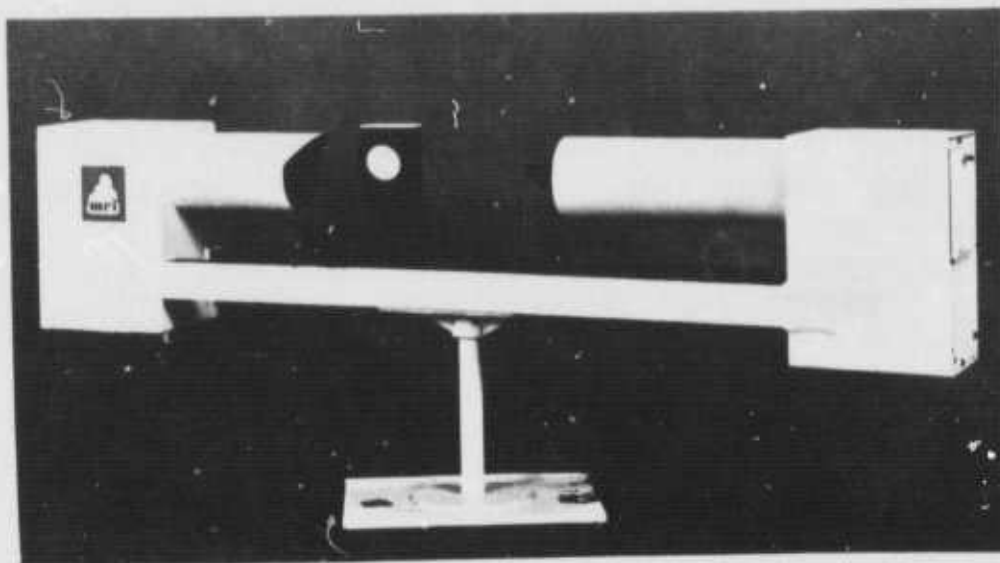


Figure 5. Fog Visiometer, MRI

receiver. The projector consists of a Xenon flashlamp which illuminates the sampling volume through an opal diffusion glass filter. The detector is a photomultiplier tube with a field of view limited by a series of collimating apertures. The photomultiplier tube looks through the apertures into a light trap at the opposite end of the device (see Figure 6) which defines the limit of the sampling volume. The light trap and all other internal surfaces in the optical system are coated with an optical black, nonreflective finish.

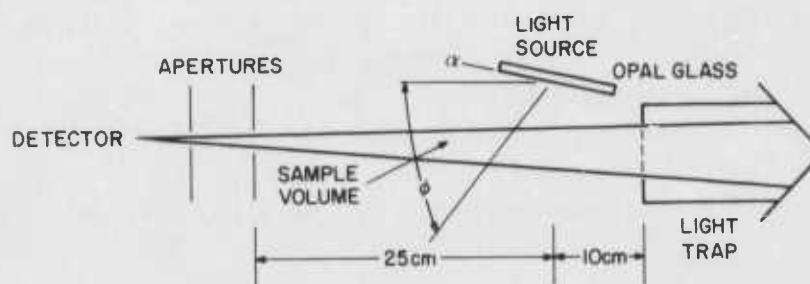


Figure 6. Schematic Diagram of Fog Visiometer

Note in Figure 6 that the opal glass filter is tilted towards the photodetector by the angle α to compensate for forward light losses in the instrument. This tilt excludes most diffracted light, concentrated in the small forward angles and very sensitive to particle size, and captures the reflected and refracted light, found in the forward angle range of 7 to 90 degrees, which is less sensitive to particle size. The tilting of the glass also adds energy to the 7 to 90 degree region thus increasing the scattered light from these angles which tends to compensate for the loss of diffracted light.

The output voltage (0 to 5V dc) is linearly proportional to the atmospheric extinction coefficient. The effective range of extinction coefficient is $50 \times 10^{-5} \text{ m}^{-1}$ to $5000 \times 10^{-5} \text{ m}^{-1}$ which corresponds to 58 m to 5.8 km daytime visibility.

3. PREVIOUS STUDIES

Comparative analyses of the instruments used in this study have been primarily limited to human observations and/or transmissometers rather than to each other. Of the three, the FSM and Videograph have been subjected to considerable test and evaluation as reflected in the published literature, whereas the Fog Visiometer has been subjected to modest evaluation at best.

A review of the evaluation of the FSM would be extensive and need not be repeated in detail. Initial tests in the summer of 1970⁵ examined the performance characteristics of the instrument through comparisons with simultaneous measurements of atmospheric extinction coefficient with a conventional transmissometer and with human observations of visibility obtained in periods of dense coastal advection fog at Cutler, Maine. A correlation coefficient of 0.91 between the FSM and transmissometer was obtained with a corresponding standard error of estimate of 26 percent. Additional comparisons in winter snow situations gave results similar to those obtained in fog conditions. Further comparisons between the FSM and transmissometers and human observations were made as part of the Hanscom mesonetwork experiments.² During periods of fog and rain in the fall of 1972, a correlation coefficient of 0.98 (and standard error of estimation of 19 percent) was found between FSMs and transmissometers at three sites in eastern Massachusetts. Considerable data have also been gathered to evaluate the long term calibration, accuracy, and representativeness of FSMs through comparisons of two instruments

5. Hering, W.S., Muench, H.S., and Brown, H.A. (1971) Field Test of a Forward Scatter Visibility Meter, AFCRL-71-0315.

mounted 3 m apart at one site in the mesonetwork.⁶ Standard errors of estimation of one FSM reading, given another 3 m away, were found to be 17 percent in radiation fog situations and 12 percent in other types of restriction. It was also found that the representativeness of the FSM measurements increases as the visibility decreases, yielding standard errors of 4 to 8 percent when the visibility is less than 3 km. In a study designed to establish a slant visual range system, encouraging correspondence has been found between tower-mounted FSMs and slant transmissometer measurements at the FAA's test facility in New Jersey.⁷

Extensive testing of the Videograph first occurred over a 2.5-yr period at the Meteorological Institute of the University of Berlin in the mid-1960's.⁸ Comparisons of Videograph measurements with carefully collected visual observations revealed errors of estimation of about 20 percent provided that no completely abnormal distribution of aerosol particles occurred. It was found, however, that the Videograph indicates a visibility lower than that actually existing in snowfall and in certain types of fog. The calibration of the Videograph by transmissometers under conditions of moderate atmospheric turbidity was found to be quite valid and reliable under other types of restrictions. An empirical calibration of the Videograph's output to visual observations was determined by the NWS⁴ based on extensive data collected at five locations from Oct 1971 through April 1973. Comparisons were made in six categories of restriction, no precipitation, rain, or snow during daylight hours and at night. In Figure 7 the calibration curves that were determined are summarized. Clearly, the markedly different calibration in snow is evident and to a certain extent rain occurring at night causes visibility readings which are lower than actual. The NWS results have been confirmed by comparable studies conducted in Canada⁹ where Videograph observations were compared with human prevailing visibility observations. These studies found a significant dependence on ambient temperature which resulted in both long and short term drifts in the sensor's calibration.

-
6. Chisholm, D. A., and Kruse, H. (1974) The Variability of Visibility in the Hanscom Mesonetwork : A Preliminary Assessment, AFCRL-TR-74-0027.
 7. Lohkamp, C. W. (1974) A slant visual range/approach light contact height system, Sixth Conference on Aerospace and Aeronautical Meteorology - Preprint Volume, pp 448-451.
 8. Vogt, H. (1968) Visibility measurement using backscattered light, JAS 25: 912-918.
 9. Sheppard, B. E., and Clink, W. L. (1974) The Videograph Calibration Experiment at Toronto International Airport, 23 November 1970 to 31 October 1971, TR-1, Environment - Atmospheric Environment Service, Canada, 22 pp.

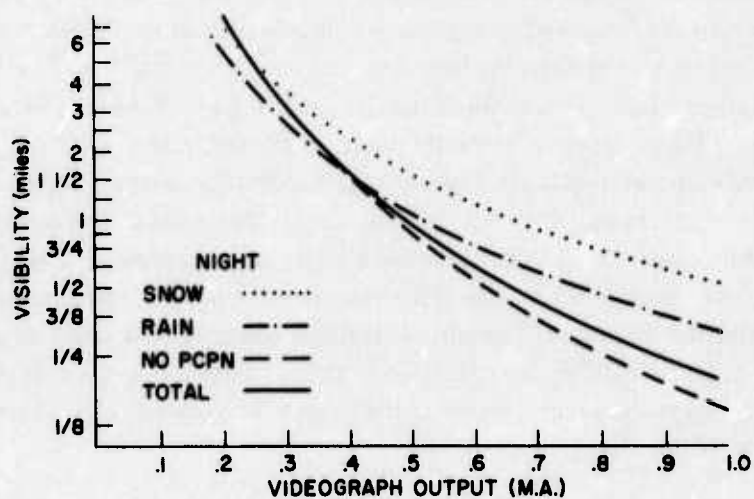
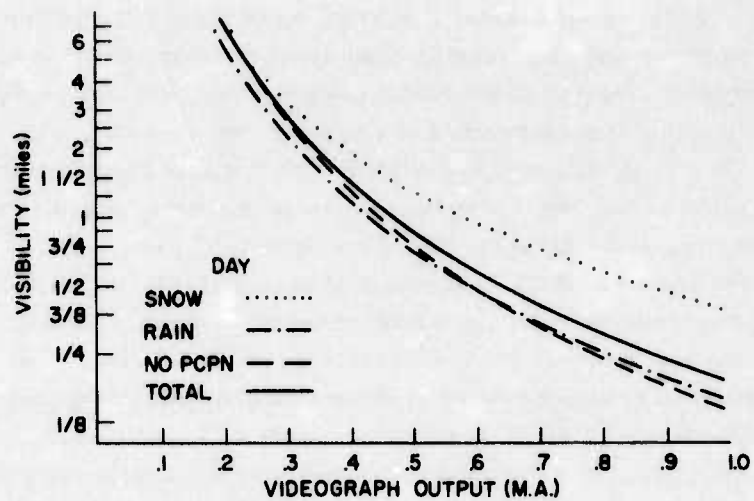


Figure 7. Videograph - Human Visibility Calibration Curves as Function of Restriction Cause - Day and Night (from NWS study⁴)

Published evidence of previous testing of the Fog Visiometer is limited. An internal memorandum report¹⁰ by the manufacturer included an evaluation of the prototype version of the Fog Visiometer versus a standard NBS-type transmissometer. An analysis of data collected in fog, at McClellan AFB, Calif.,

10. Tombach, I. (1971) An Interim Evaluation of the MRI Model 1580 Fog Visiometer, MRI 71 M-966.

revealed a correlation of 0.93 based on 165 pairs of 5-min mean observations. An examination of the applicability of the Fog Visiometer and other devices to highway fog problems was conducted in California.¹¹ The results of that test are limited because of the lack of dense fog at the test site. The report did conclude that the Fog Visiometer showed promise because of its ability to detect very dense fogs while the other devices could not.

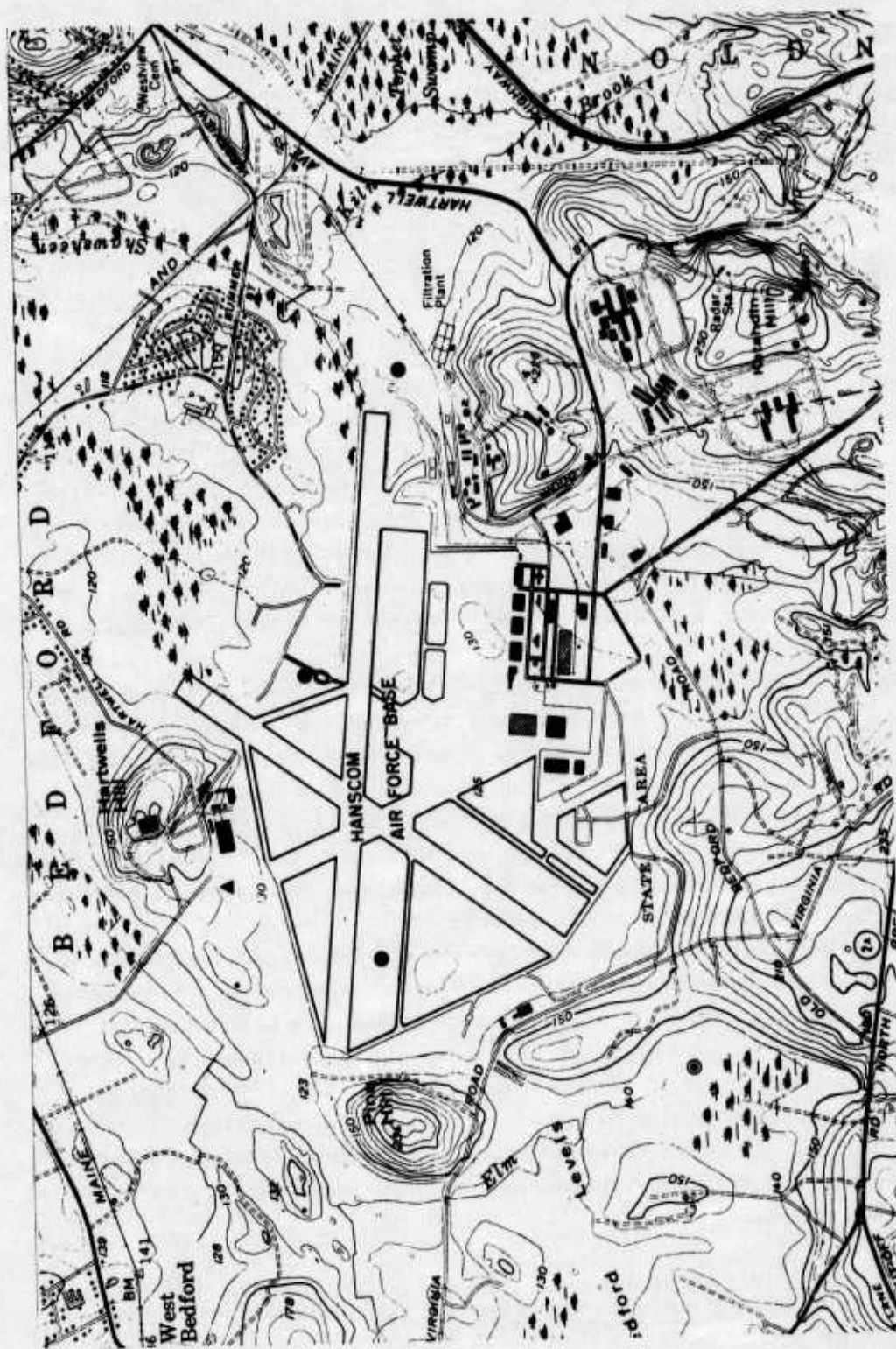
4. DATA COLLECTION PROGRAM

The three visibility sensors were mounted on top of a 7-m pole located roughly 1.5 km southwest of the intersection of the two runways on Hanscom AFB, Mass. (see Figure 8). The site is on the extremity of a sanitary landfill bordering a marshy wetland area which extends to the south and west of the site. The base of the pole is on filled ground about 4 m above the marsh elevation thereby placing the sensor volumes about 12 m above the marsh. Additional FSMs are located at three points along the main runway (11 to 29) at Hanscom and on a tower located 550 m north of the runway and about 2 km from the test site. The measurements from these locations provided the checks for the FSM reading at the test site.

The configuration of the three scatter meters on the pole is shown in Figure 9. The FSM, on the left, is at the east end of the crossarm, the Fog Visiometer at the west end, and the Videograph samples the region to the north of the pole which is away from the marshy area. The distances separating the centers of the respective sampling volumes are 3.5 m from the FSM to the Fog Visiometer, 6.1 m from the FSM to the Videograph, and 5.8 m from the Fog Visiometer to the Videograph. Note also the presence of a Climatronics wind speed and direction set and an EG+G temperature - dewpoint sensor.

The data from the test site were collected and processed along with all the other data in the Hanscom mesonetwork. Therein, observations are obtained six (6) times per minute, transmitted over telephone lines to a central processing site, checked for consistency and validity, and stored on magnetic tape. The mesonetwork is operated essentially on a continuous basis, thus checks for instrument performance could be made as frequently as necessary. Observational data from the three sensors were collected from 14 Nov 1974 through 8 April 1975. Difficulties with the Videograph detector precluded useful data for a 15-day period in mid-December.

11. Bemis, G.R., Pinkerman, K.O., Shirley, E.C., and Skog, J.B. (1973) Detectors for Automatic Fog-Warning Signs, California Division of Highways, CA-DOT-TL-7121-1-73-22.



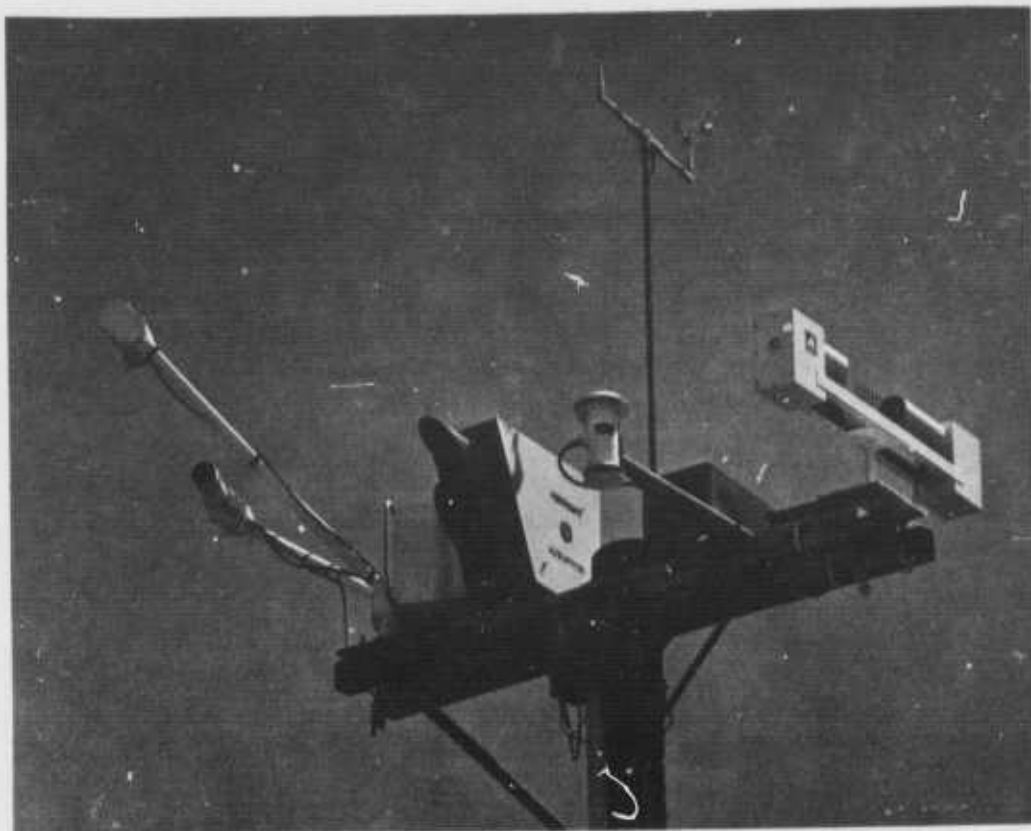


Figure 9. View of Three Scattering Meters on Pole at Test Site.

A useful collection of over 4 months was achieved. During that period there were numerous occasions of extended restrictions to visibility due to continuous rain and/or snow, showers, stratus and drizzle, and haze and fog. Seven percent of the four month period found extinction coefficient values at the test site greater than $10 \times 10^{-4} \text{ m}^{-1}$ (daytime visibility of 3 km or less).

5. DATA ANALYSIS

The method of analysis considered two problems initially and then a third problem which became apparent as the study proceeded. The initial problems related to (1) the calibration of the Videograph to the FSM as a function of restriction cause and time of day and (2) the correlation of the three sensor measurements to one another as a function of cause and time of day. The problem that developed related to the "recalibration" of the Fog Visiometer to the FSM.

5.1 Videograph Calibration

The calibration studies conducted by the NWS yielded equations which relate the Videograph output in milliamperes to visual observations in statute miles. In order to be compatible with the mesonetwork processing system, the Videograph electronics package was modified to generate voltage output (0 to 5 V full scale). Thus, calibration equations developed in this study relate Videograph output in volts to FSM extinction coefficient in units of 10^{-4} m^{-1} . Based on the NWS experience, separate calibration equations were developed for rain, snow, and non-precipitation for both day and night and a generalized day vs night separation was also considered. We chose to conduct the calibration evaluation in a manner similar to the NWS study.

The expected relationship between the Videograph output voltage (V) and atmospheric extinction coefficient (σ), given the empirical basis for and design of the instrument, would be

$$\sigma = aV^b,$$

where a and b are constants. In Table 1 the calibration constants that were derived for each weather restriction cause are listed.

Table 1. Videograph Calibration Equations

Restriction Cause	Sample Size	$\bar{\sigma}$ (10^{-4} m^{-1})	Equation
Rain-Day	1279	28	$\sigma = .00055V^{1.86}$
Rain-Night	2365	32	$\sigma = .00052V^{1.84}$
Snow-Day	1600	27	$\sigma = .00021V^{2.16}$
Snow-Night	1172	16	$\sigma = .00067V^{0.93}$
No Prec-Day	86	21	$\sigma = .00042V^{2.08}$
No Prec-Night	2124	31	$\sigma = .00045V^{2.19}$
Total-Day	2965	27	$\sigma = .00052V^{1.59}$
Total-Night	5661	28	$\sigma = .00050V^{1.81}$

With the exception of daytime periods of restricted visibility without precipitation, there was considerable data available to derive the calibration equations. The data used were 1-min mean values determined from six observations 10-sec apart. In total then the daytime sample comprised nearly 50 hr of observations and the night sample over 90 hr. The equation development was limited to those individual minutes in which the FSM recorded an extinction coefficient of $10 \times 10^{-4} \text{ m}^{-1}$ or greater (in other words, a daytime visibility of 3 km or less). Thus the sample mean values ($\bar{\sigma}$) shown reflect the distribution within bounded subsets of extinction coefficient. With the exception of snow, nighttime conditions are slightly more restrictive (higher average extinction) than daytime for a given restriction cause. This is consistent with the overall climatology of restricted visibility that has been determined from observations taken in the mesonetwork over a 30-month period which includes three winter seasons. Diurnal variability of extinction is least during the winter months ranging from a peak of 8.0 percent during the period 3 to 6 hr before sunrise and a minimum of 5.9 percent 9 to 12 hr after sunrise. In Figures 10 and 11 the equations for the 3 subsets from Table 1 for night and day, respectively, are plotted. Clearly, the calibration of the Videograph is considerably different during periods of snow as compared with rain and nonprecipitating restriction periods. This concurs with the previous findings of the NWS,⁴ the Canadians,⁹ and the studies in Berlin⁸ discussed earlier. The difference between rain and nonprecipitation, both day and night, is slight. Similarly, there is little difference day vs night for periods of rain and for periods of nonprecipitation.

The markedly different calibration in snow presents a special problem in that reliable, automated techniques do not presently exist to discriminate the occurrence of snow from other types of restrictions. The problem is further complicated by the fact that the calibration appears to be dependent on the type and intensity of the snowfall. In Figure 12, calibration curves for data drawn from 4 separate daytime snow periods are shown. The calibration curve for 5 Feb 75 reflects a more enhanced signal from the Videograph than occurred on other days. The snow falling on that day was of moderate to heavy intensity and was dry and powdery due to air temperatures around -5°C . Conversely, the snow which fell on 9 Jan 75 was of light intensity and wet in that the air temperature was near 0°C and the snow occurred after a period of rain. On 7 Jan 1975 the snowfall was of moderate intensity with temperatures around freezing, and that of 25 Dec 1974 was light to moderate dry snow. Thus the Videograph signal seems to be enhanced by increased snowfall intensity and by the degree of dryness of the snow as reflected by the air temperature.

The enhanced signal causes the sensor to reach its capacity (maximum return) at a lower extinction coefficient (or higher visibility) than would be the case during

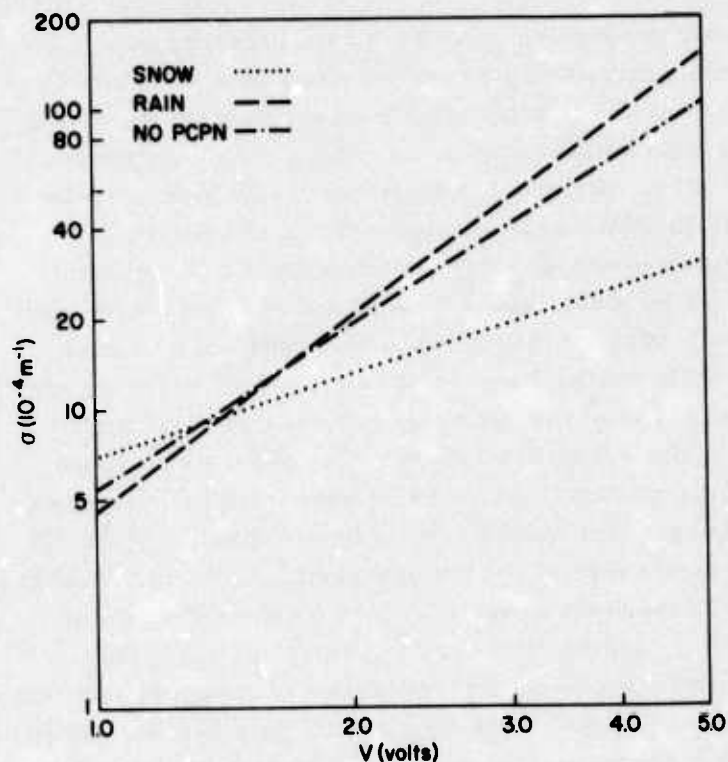


Figure 10. Videograph -
FSM Calibration Curves as
Function of Restriction
Cause - Night

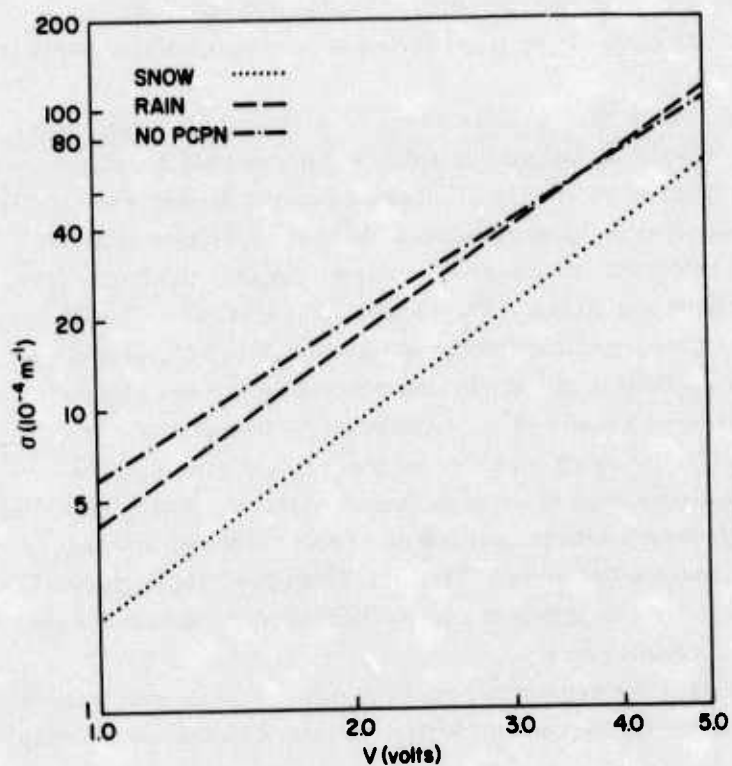


Figure 11. Videograph -
FSM Calibration Curves as
Function of Restriction
Cause - Day

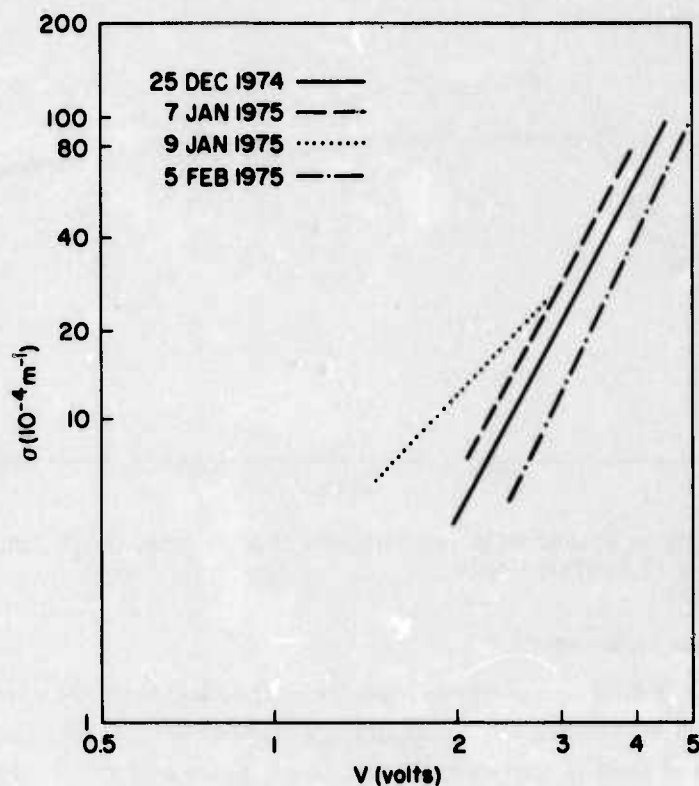


Figure 12. Videograph - FSM Calibration Curves During 4 Daytime Snow Episodes

other types of restrictions. Thus, its capability or utility is more limited in snow regimes since the lower, more critical visibility ranges may not be sensed. This is illustrated in Figure 13, which is time series plots of extinction coefficient from the FSM and the Videograph during a brief snowstorm of 18 Feb 1975. The Videograph sensing capability became saturated at a daytime visibility of just under 400 m (0.25 mi) (FSM extinction coefficient of $90 \times 10^{-4} \text{ m}^{-1}$) which would be acceptable at a Category I type airfield, of marginal value at a Category II airfield, and inadequate at a Category III airfield where measurements down to 50 m could be required. The problem is compounded if one considers the nighttime situation where, with light setting 5 conditions, the extinction coefficient corresponding to Videograph saturation would yield a visibility of about 2 km (1.25 mi) which would not even satisfy Category I landing requirements.

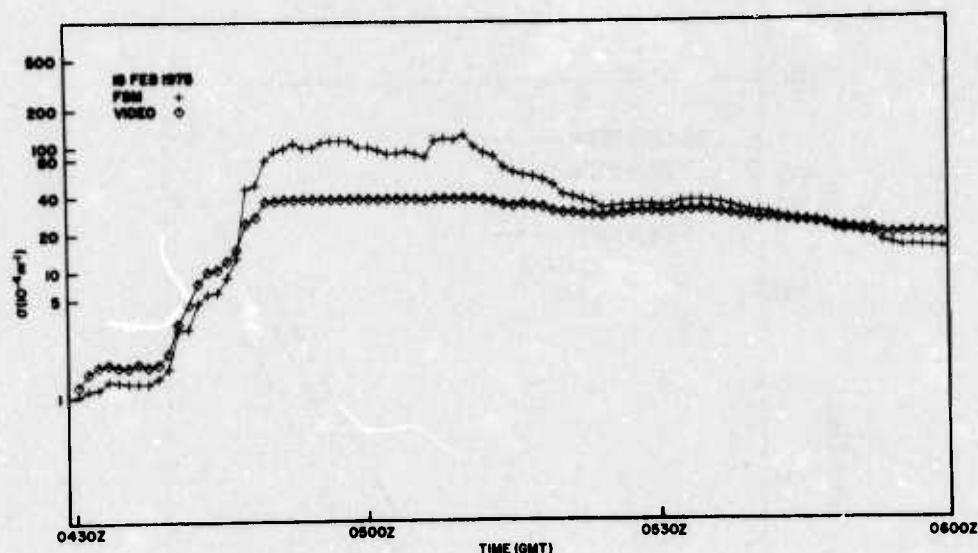


Figure 13. Time Plot of FSM and Videograph Extinction Coefficient During Snowstorm of 18 February 1975

5.2 Fog Visiometer Calibration

Evaluation of the Fog Visiometer has revealed that there are certain weather situations which seriously limit its utility. The most serious problem develops during periods of snow preceded by rain. Visits to the test site during periods of snow revealed that the optical black, nonreflective surface of the light trap at the far end of the sampling volume was collecting snowflakes thereby altering its optical properties. As a result, the "sensed" extinction coefficient becomes unrealistically high as shown in Figure 14, which is time series plots of extinction coefficient (10^{-4} m^{-1}) from the Fog Visiometer and the FSM during a period of wet snow that fell on New Year's Eve (1 Jan 1975). The Visiometer functioned properly during the first 1.5 hr of the storm, then steadily rose to a full 5.0-V (or $500 \times 10^{-4} \text{ m}^{-1}$) reading before 0400Z. Though not shown on the plot, it continued to read full scale for over 4 hrs before slowly returning to readings comparable with the FSM. The period of return to normalcy coincided with a slight warming to above freezing temperatures and a change to light rain or drizzle which undoubtedly cleansed the light trap surface and returned it to its designed optical properties.

Adherence of snow to the instrument surfaces bounding the sampling volume has been found to be most severe during periods when the temperature is close to freezing. The problem rarely appears when the snow is dry and of light intensity. However, dry snow of moderate to heavy intensity that falls over a several-hour period will accumulate around the "bird-spikes" which are mounted on the

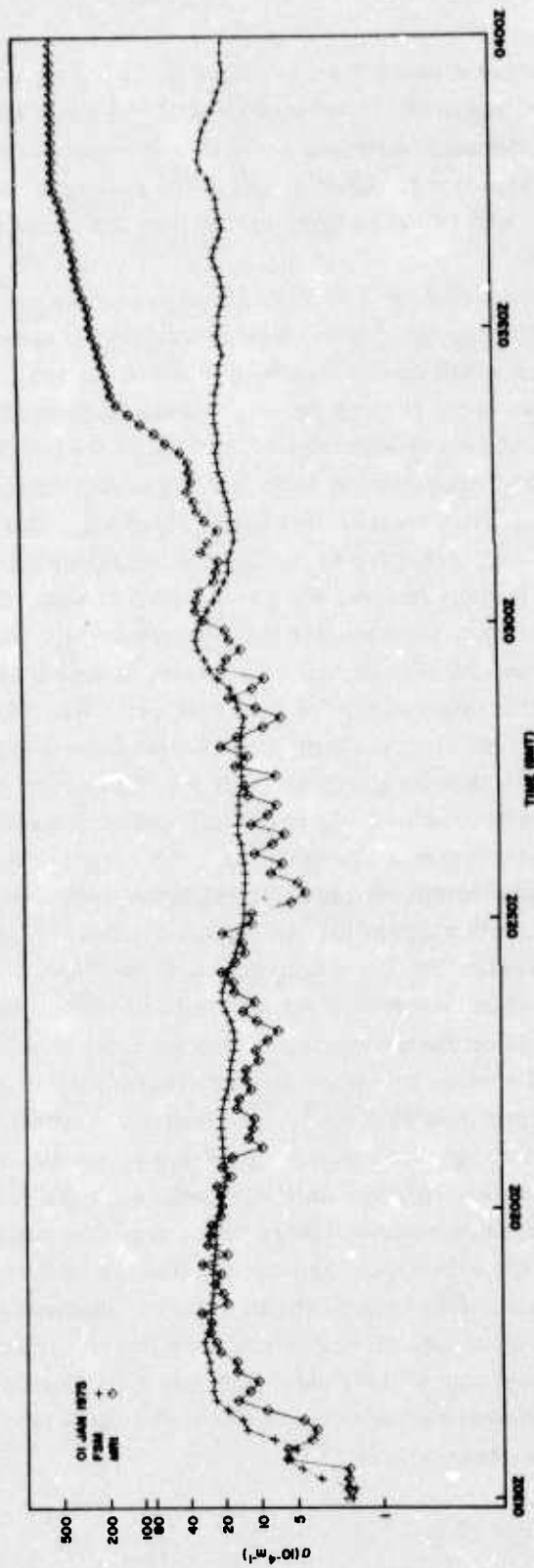


Figure 14. Time Plot of FSM and Fog Visiometer Extinction Coefficient During Snowstorm of 1 January 1975

base of the unit to prevent birds from perching in the sampling volume. As the snow accumulates in this area, it creates an artificial white reflective surface which alters the scattering properties and yields an enhanced return from the sensor. In the extreme it will result in full-scale readings, generally it results in readings that range 25 to 100 percent higher than the companion FSM and Videograph readings.

The sampling volume of the Fog Visiometer is considerably smaller than that of the FSM and the Videograph. While this characteristic does not cause any particular problem in small particle restrictions such as fog, drizzle, and haze, it can result in rather noisy (widely varying) signals in periods of light rain. During periods of light rain (visibilities of 2 to 10 mi) the number concentration of raindrops, with typical diameters of 0.05 to 0.1 cm, can vary over a fairly wide range at the instances when measurements are recorded. The scattering properties become increasingly sensitive to the number concentration as the sampling volume decreases. In the extreme, the presence or absence of one or two large droplets can result in extinction coefficient measurements varying over a range of ± 100 percent. This can be seen in Figure 15 which is time plots from the Fog Visiometer and FSM during a period of light rain on 21 Mar 1974. As the rain intensity and its corresponding extinction coefficient increases, the noisiness of the observations diminishes as shown towards the right end of the plot.

The Fog Visiometer was initially calibrated and periodically rechecked using the manufacturer's recommended procedures. The output voltage is designed to be linearly proportional to the atmospheric extinction coefficient. The data collected in our experiments suggest that an adjustment must be applied to the Fog Visiometer output to make it more compatible with the FSM.

An examination of comparative FSM and Fog Visiometer output revealed that the recalibration could be adequately handled by grouping the steady rain data with the advection fog and stratus data provided the observations were limited to extinction coefficients greater than $10 \times 10^{-4} \text{ m}^{-1}$. Such a limitation removed from the analysis the situation of light rain which yields noisy, poorly correlated observations from the Visiometer. All the snow data were excluded for the reasons cited earlier. Three calibration equations were developed: day, night, and all times. They are shown in Figure 16 which includes the line (dashed) of perfect correspondence with the manufacturer's calibration curve. Basically these data show that the Visiometer output depicts better visibility (lower extinction coefficient) than in fact exists according to the FSM. There is a fairly modest difference between day and night wherein the daytime readings reflect better visibility than comparable nighttime observations.

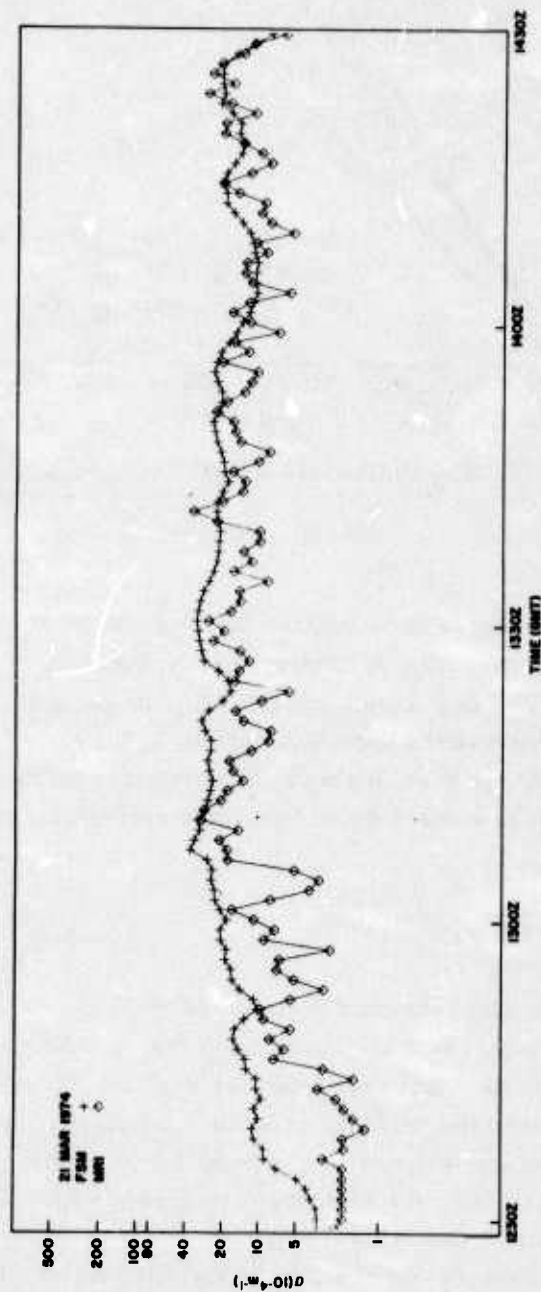


Figure 15. Time Plot of FSM and Fog Visiometer Extinction Coefficient During Rain of 21 March 1974

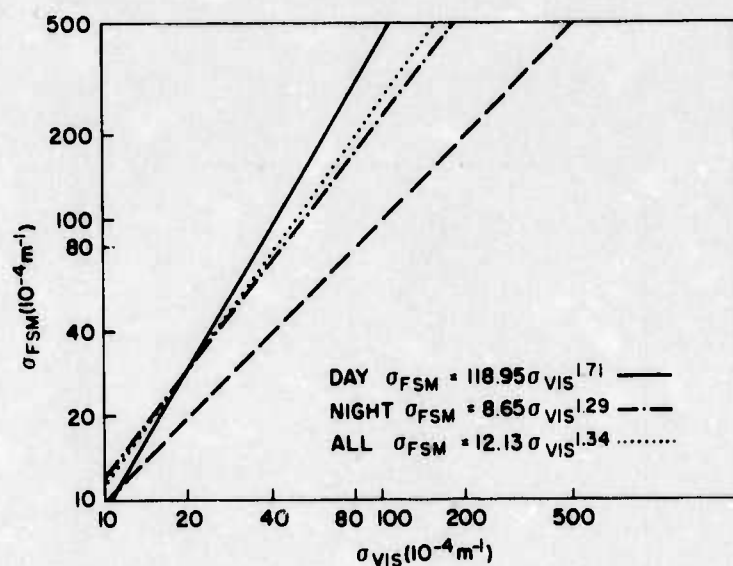


Figure 16. Fog Visiometer - FSM Calibration Curves

5.3 Correlation Analysis

An analysis of the correlation between the three sensors was conducted for all periods where the extinction coefficient, as measured by the FSM, was greater than $10 \times 10^{-4} \text{ m}^{-1}$. The data were stratified by restriction cause and by time of day. Finally, the observations were transformed to log form for the analysis because visibility data are more normally distributed in log form. The standard error of estimation (SE) was computed from each correlation coefficient (r) through

$$SE = (1 - r^2)^{1/2} PD ,$$

where PD is the percentage standard deviation of the within-sample FSM or Fog Visiometer observations. In Table 2 are listed the correlation coefficients and associated standard errors that were found for each stratification. Correlations involving the Fog Visiometer were not calculated for snow episodes nor were they calculated for the "no precipitation-day" period due to a temporary malfunction of the instrument. Recall from the Videograph calibration section that there were just 86 minutes of data in that subgrouping.

The correlation between observations is highest (and the SE lowest) when visibility is restricted without precipitation falling. This can be attributed to a more uniform distribution of water droplets concentrated in a fairly narrow drop-size

Table 2. Correlation Coefficient (r) and Standard Error of Estimation (SE) Between FSM, Videograph (VID), and Fog Visiometer (VIS)

Restriction Cause	FSM vs VID		FSM vs VIS		VID vs VIS	
	r	SE (%)	r	SE (%)	r	SE (%)
Rain-Day	.94	32	.89	43	.87	24
Rain-Night	.87	47	.85	51	.77	40
Snow-Day	.83	32	--	--	--	--
Snow-Night	.60	30	--	--	--	--
No Prec-Day	.95	16	--	--	--	--
No Prec-Night	.95	23	.94	28	.90	26

distribution in stratus and fog. Recall that the distance between the sensing volume centers ranges from 3.5 m from the FSM to the Visiometer, to 6.1 m from the FSM to the Videograph. FSM's mounted 2.6 m apart at the east end of the Hanscom AFB runway yielded standard errors ranging from 4 to 7 percent during periods of rain, snow, and advection fog,¹² which are considerably smaller errors than the results found here. Although the respective sampling periods were different and the observations were collected at locations about 2.5 km apart, the results should be comparable because of the abundant amounts of data included in each test.

6. CONCLUSIONS

The forward scatter meter (FSM) has undergone extensive testing and evaluation prior to and during the Hanscom mesonetwork experiments. Over 100 instrument-years experience has been accumulated with it and from that experience we have concluded that it provides reliable, accurate, and representative measurements of atmospheric extinction coefficient at a point location in all kinds of restrictions. Comparisons made with 250- and 500-ft path-length transmissometer data and human visibility observations support the contention that a point measurement is highly correlated to a line or area measurement except in highly variable conditions such as patchy ground fog. In addition, the maintenance and repair requirements of the FSM are modest as reflected by a mean time between failures (MTBF) which exceeds one year.

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The tests presented in this report were conducted for the purpose of providing data that would allow an objective evaluation of the FSM as compared with two other commercially available scattering-type visibility meters, the Videograph and the Fog Visiometer. These tests have led to the following conclusions:

(1) The Videograph and the Fog Visiometer have a consistent calibration with the FSM during periods of fog and stratus and in rain although the Visiometer can be somewhat erratic in light rain.

(2) The Fog Visiometer has limited usefulness during snow, particularly when the air temperature is close to the freezing mark.

(3) The calibration of the Videograph to the FSM in snow is markedly different than with other kinds of restrictions due to enhancement of the backscattered signal off the snowflakes.

(4) The Videograph becomes saturated (reads full scale) in snow when the visibility is reduced below about 400 m (0.25 mi) daytime or 2 km (1.25 mi) nighttime.

(5) During the period of the test, all three instruments performed well with just two brief periods of downtime due to component failure.

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